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A NEW ELECTROCARDIOGRAPHIC DETECTION PROCEDURE FOR FETAL HEART RATE MONITORING

by

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THESIS

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CHAPTER 1

INTRODUCTION

In 1973, there were 25 perinatal deaths per 1000 births in the United States [1]. A study conducted in 1958 in England (which has a similar number of perinatal deaths) indicated that 31% of the deaths were due to intrapartum anoxia and 17% due to antepartum anoxia [2]. A severe deficiency in the quantity of oxygen carried by the fetal blood caused almost half of the perinatal deaths.

The effect of fetal hypoxia on perinatal morbidity has yet to be quantified. However, low oxygen concentrations can subtly compromise the central nervous system retarding intellectual development.

Fetal monitoring has become widespread and there are many types of monitoring methods to assess the various factors which indicate the degree of fetal well-being. The majority of these methods are used in the intrapartum period, but there has been a rapid increase in the use of antenatal techniques to identify fetal populations at risk. Identification of such populations is necessary for the administration of appropriate obstetric care.

Analysis of the changes in fetal heart rate (FHR) has become an accepted technique of screening for the potentially distressed (hypoxic) fetus either during labor or during gestation. The classification of these changes in the FHR can be divided into three domains: periodic patterns (decelerations or accelerations in the "baseline" usually caused by uterine contractions or fetal movement), long-term variability (rhythmatic flucuations of 2 to 6 cycles per minute), and short-term variability (beat-to-beat changes). While the analysis of periodic patterns offers much clinically useful information, it appears the data which will

elucidate the underlying events associated with fetal hypoxia and give a more sensitive indication of the degree of hypoxia will come from analysis of variability, especially short-term variability (STV) [3, 4].

The present methods of FHR monitoring (commonly ultrasonic, phonocardiographic, or electrocardiographic) can provide a clinically acceptable record for the analysis of periodic patterns and sometimes long-term variability (LTV). Only recently has there been sustained efforts to improve these cardiotachometric techniques so that STV can be more accurately assessed.

The motivation for the research described in this paper was the need for an improved fetal heart beat detection procedure which would allow for accurate determination of STV during the antenatal period. The next chapter of this thesis examines fetal physiology with regards to the factors which influence the FHR and their manifestations in the FHR record. The following chapter reviews present FHR monitoring techniques. The detection procedure used in this research is described in detail in the fourth chapter. Conclusions and further research possibilities are discussed in the final chapter.

CHAPTER 2

FETAL PHYSIOLOGY: FACTORS INFLUENCING FETAL HEART RATE AND THEIR MANIFESTATIONS[1]

2.1 Physiologic Control of Fetal Heart Rate

The physiologic control of FHR is a complex interation of many factors (see Appendix I). The myocardium possesses an intrinsic rhythmatic contractility which is mediated by a "reflexive" influence and the direct influence of the physiologic environment on the heart tissue. This interaction produces an average FHR at 20 weeks of 160 beats per minute (bpm) and at term of 140 bpm. The normal range is from 120 to 160 bpm, but some healthy fetuses have an average value outside the range. The maximum beat-to-beat fluctuation is 25 bpm.

The reflexive influence is effected via the parasympathetic and sympathetic innervation of the heart (i.e., the vagus nerve and cardiac nerves of the cervical ganglia, respectively). Generally, the vagal influence on the heart is to decrease rate and increase variability. The sympathetic influence is to increase rate. The parasympathetic and sympathetic nerves interact causing beat-to-beat adjustments in the fetal heart rate thereby maintaining an average FHR. This "baseline" rate reflects the tonic balance, and therefore baseline variability is important as an indication of active central nervous system (CNS) integrative capabilities.

The parasympathetic and sympathetic influences on the FHR arise from the integration of many interactions in the peripheral and central

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[1] Much of the material in this chapter is from Tucker [1] and from Martin and Gingerich [5].

nervous systems (Figure 1). The vagal and cardiac nerves have communicating processes between themselves to facilitate interaction before reaching the heart tissue. The nuclei of these nerves reside in the brain stem allowing for interaction with other nerves of the peripheral and central nervous systems. For example, fetal movements (potentially initiated in the CNS) or external tactile stimulation (sensed by the peripheral nerves) can result in an increase in heart rate and sometimes an increase in heart rate variability.

Changes in blood pressure, sensed by the carotid or aortic baroreceptors, will also influence the tonic balance. Rising pressure will result in increased stimulation of the vagus thereby decreasing heart rate and increasing heart rate variability. Falling pressure first decreases stimulation of the vagus. If the pressure continues to drop, it results in increased stimulation of the sympathetic nerves and increased heart rate.

Chemoreceptors, some of which are located in the medulla and others in the carotid and aortic bodies, monitor the concentration of oxygen, carbon dioxide, and acid. An acute decrease in oxygen concentration near to or below critical levels will result in vagal stimulation when sensed by the chemoreceptors. This will cause a decrease in heart rate and an increase in variability. Mild or chronic low oxygen concentrations near to the critical levels will lead to sympathetic stimulation and suppression of vagal tone. Hence, heart rate will rise and variability lessen. In either case, if severe hypoxia persists, the CNS will become depressed, weakening the reflexive influence on the FHR.

The chemoreceptors have little direct effect on the vagal and sympathetic nerves if changes in oxygen concentration are sensed when the concentration is above critical levels. However, the chemoreceptors do

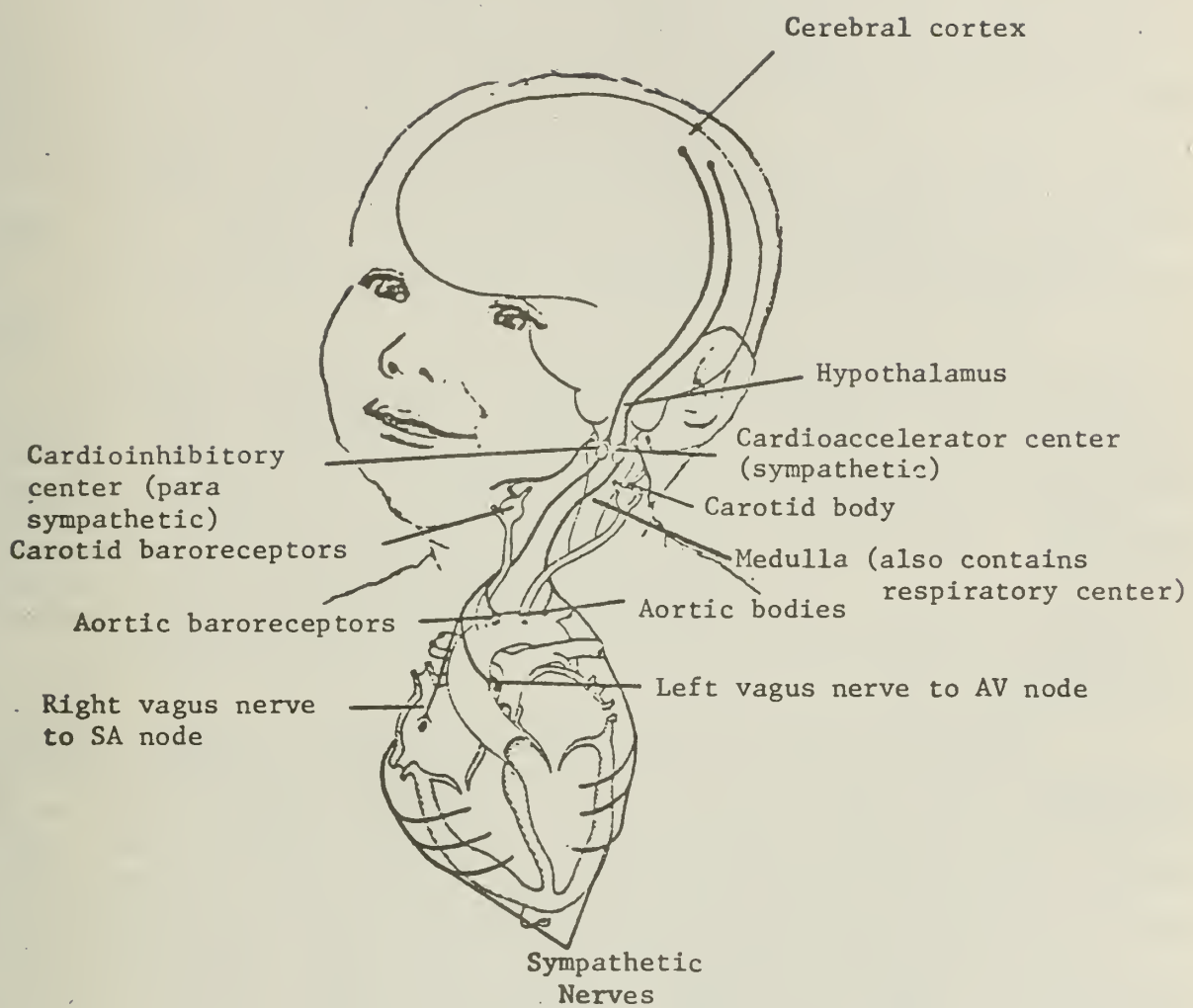


Figure 1. Scheme of reflexive mediation of fetal heart rate. (Modified from Tucker [1])

influence the respiratory center in the medulla when such changes are detected. If there is a decrease in oxygen concentration (or increase in carbon dioxide concentration), the center increases the frequency of respiration. The efferent nerves used to initiate the act of inspiration interact with the vagal efferents to the heart and block their activity. Vagal activity is reinstated during expiration. Therefore, the respiratory center contributes a periodicity to heart rate changes (called sinus or respiratory arrhythmia) which is sensitive to changes in oxygen concentration when the concentration is above critical levels [4].

When severe hypoxia persists, it will directly influence the pacemaker and cardiac muscle cells by depressing their inherent rhythmicity. This direct influence will override the weakened reflexive influence. In this state, heart rate and variability will both decrease. A low heart rate with little variability signifies extreme fetal distress and impending death.

Influences on FHR via the reflexive and direct pathways combine and adapt the intrinsic heart rate to a continuum of hypoxic states. As an example, chronic hypoxia of increasing severity will first increase heart rate and decrease variability due to stimulation of the cardiac nerves and suppression of vagal tone. With the onset of anoxia, heart rate and variability will decrease in response to the direct influence on the myocardium.

2.2 External Factors and Periodic Changes

External factors influencing the FHR include tactile stimulation, head compression, uteroplacental insufficiency and umbilical cord compression. These factors can give rise to the periodic patterns seen in fetal heart rate tracings. The patterns are accelerations, early

decelerations, late decelerations, and variable decelerations, respectively.

If any of the decelerations occur, it is usually during uterine contractions. Each of these three decelerations result in decreased fetal oxygen concentration. However, often the oxygen concentration does not drop below the critical level and therefore the respective deceleration pattern might not be found in the cardiotachogram.

Transient accelerations in the FHR baseline are for the most part beign (Figure 2). They are usually attributed to tactile stimulation of the fetus.

Early decelerations are a result of compression of the fetal head (Figure 3). This reduces blood flow and local hypoxia develops within the brain. The chemoreceptors of the medulla detect the decreased oxygen concentration and initiate a decrease in heart rate.

Late decelerations are a manifestation of reduced maternal blood flow through the placenta, i.e., uteroplacental insufficiency (Figures 4 and 5). Oxygen concentrations must fall below the critical level before the heart rate begins to decrease. The difference between the amount of oxygen carried by the fetal blood and this critical level is referred to as the fetal "reserve". This reserve, in addition to a progressive increase in uterine pressure which results in a slowly diminishing maternal blood flow, give rise to the late onset. Reverse processes cause the slow recovery.

Variable decelerations are attributed to cord compression (Figure 6). It is believed that there is both a chemoreceptor and baroreceptor component contributing to this deceleration.

2.3 Variability as an Indicator of Physiologic State

The concept of a fetal reserve is very important when

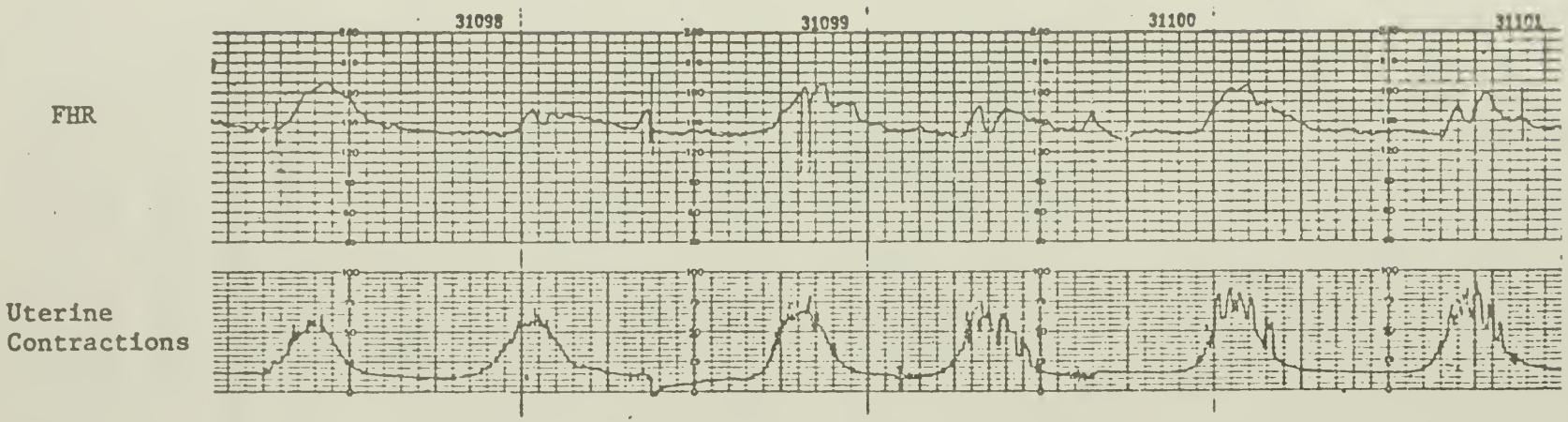
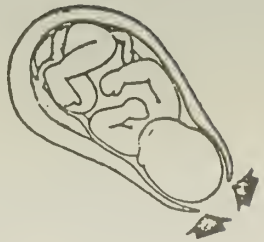


Figure 2. Accelerations. (From Martin and Gingerich [5])



Head compression (HC)

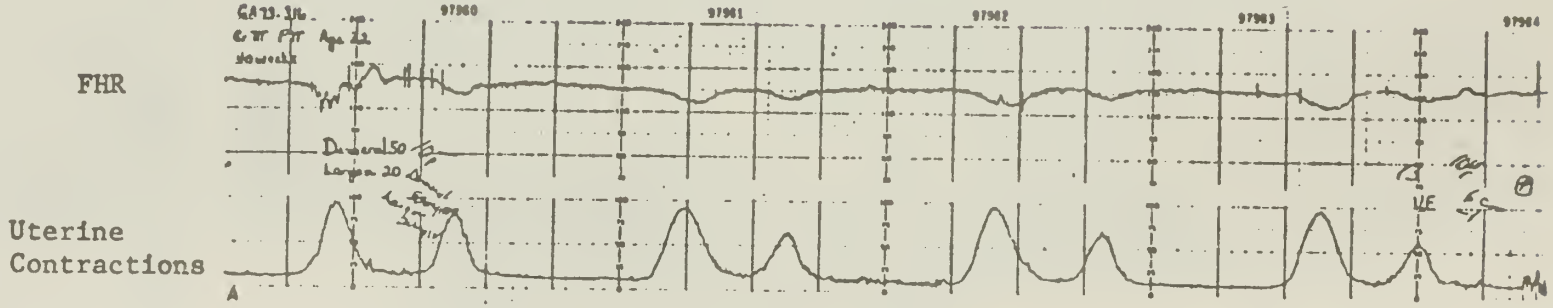


Figure 3. Early decelerations. (From Tucker [1] and from Martin and Gingerrich [5])

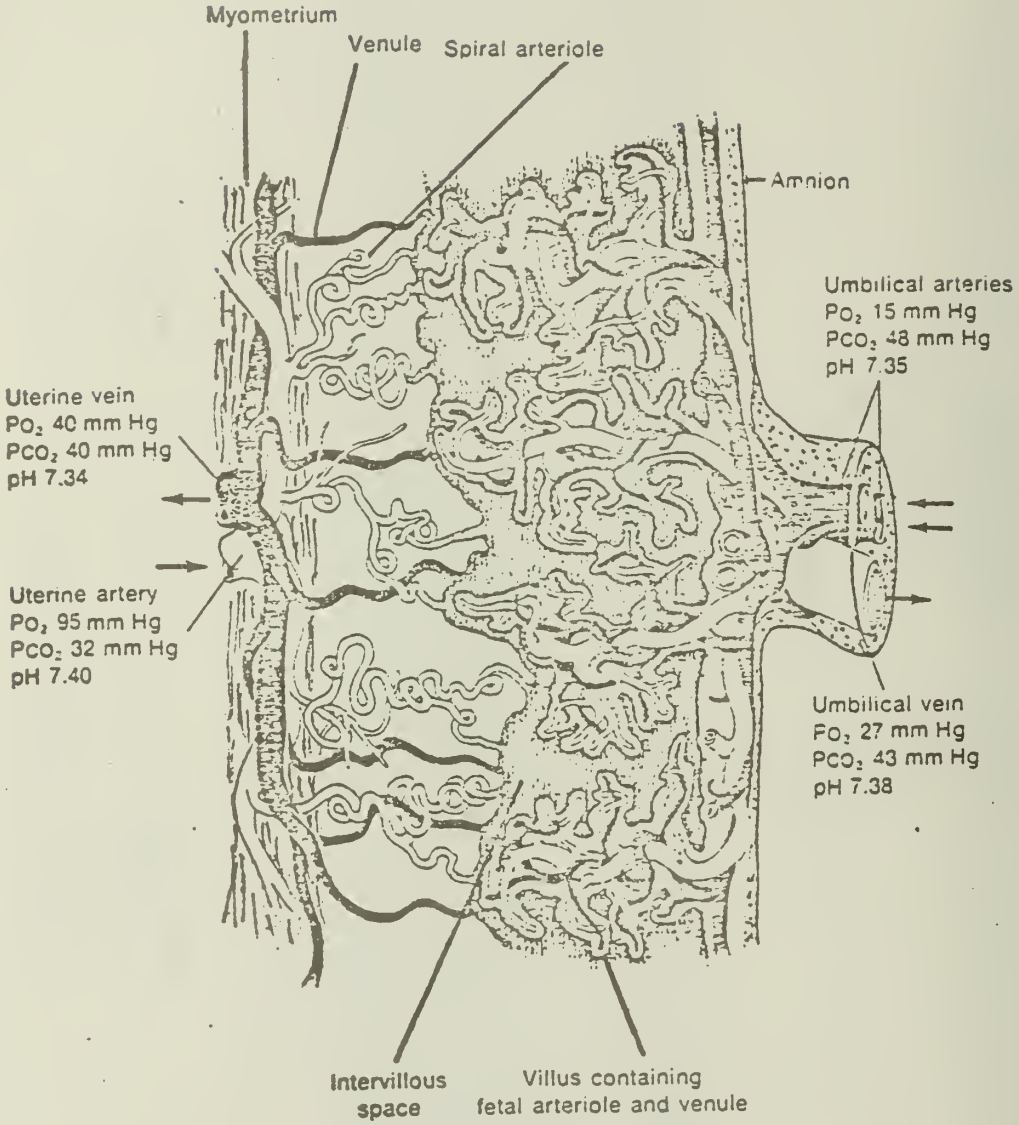
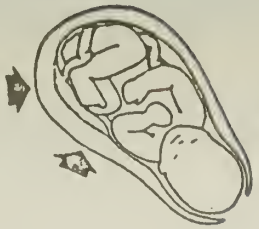
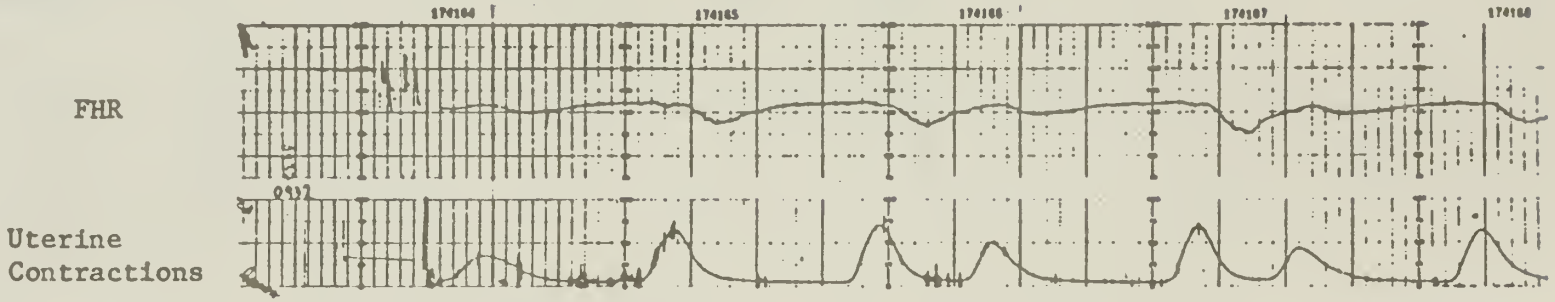


Figure 4. Schema of placenta. (From Martin and Gingerrich [5])



Uteroplacental insufficiency
(UPI)

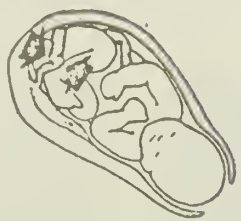


CHARACTERISTICS
- LATE ONSET - LATE RECOVERY
- U - SHAPED
- MIRROR U.C. INTENSITY
- REPETITIVE

MECHANISM
- HYPOXIA
- DIRECT MYOCARDIAL DEPRESSION
- REFLEX ELEMENT IN ACUTE HYPOXIA

SIGNIFICANCE
- INADEQUATE MATERNAL-FETAL EXCHANGE

Figure 5. Late decelerations. (From Tucker [1] and from Martin and Gingerrich [5])



Cord compression
(cc)

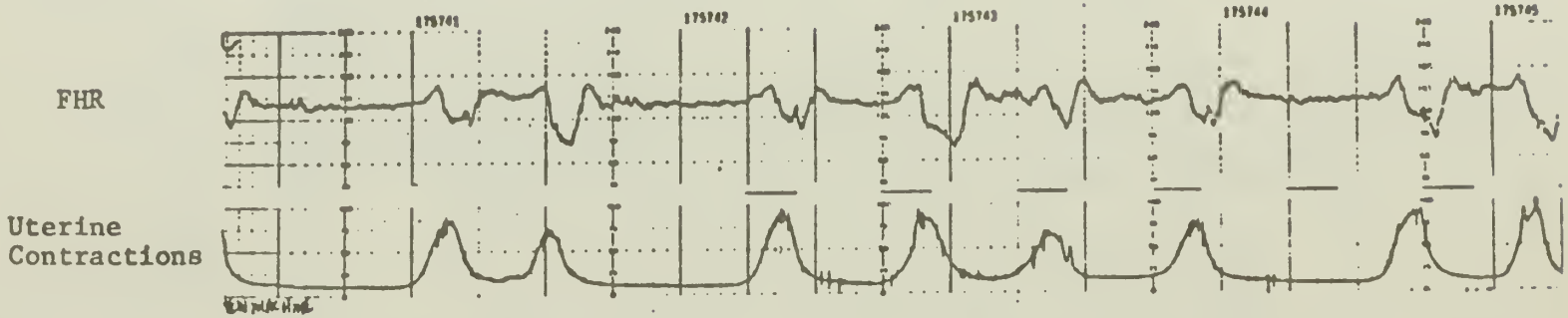


Figure 6. Variable decelerations. (From Tucker [1] and from Martin and Gingerrich [5])

distinguishing high risk fetuses from those with no or low risk. Two mechanisms can give rise to the decreased heart rate found in late decelerations: the direct one of low oxygen concentration depressing the intrinsic rhythmicity of the myocardium and the reflexive one resulting from chemoreceptor stimulation by acute hypoxia. As stated earlier, these two mechanisms combine and adapt the intrinsic heart rate to a continuum of hypoxic states. At one extreme is the fetus with a good reserve of oxygen whose FHR tracing shows good variability indicating an active CNS. In this case late decelerations indicate the fetus is experiencing acute hypoxia resulting in a pimarily reflexive influence on the FHR. At the other end is the fetus with marginal, if any, reserve whose cardiotachogram tracing shows little variability indicating a depressed CNS (see Figure 5). In this case, late decelerations are the result of the direct mechanism.

The high risk populations which we attempt to identify with FHR monitoring are those fetuses with marginal or no oxygen reserve. While analyzing periodic patterns and changes in the baseline is often clinically useful in ientifying high risk fetuses [1, 2, 5, 6, 7], a decision cannot always be made from these analyses. For example, when the fetus first begins to enter a hypoxic state sometimes decelerations do not occur during uterine contractions. In order to have a strong, less subjective basis on which to make a decision concerning fetal well-being, researchers are now studying FHR variability [3, 4, 8, 10, 11, 12].

The following are some observations concerning FHR variability. Variability usually is inversely proportional in its relationship with rate, i.e., as rate increases variability decreases. This can be explained by an increase in sympathetic stimulation of the myocardium and a decrease in vagal tone. This decrease in vagal tone is found during chronic hypoxia or prolonged anoxia. Long-term and short-term variability usually increase

or decrease simultaneously, however, there are exceptions (Figure 7). Often during fetal sleep periods, LTV diminishes but STV is maintained. In the hypoxic fetus, sometimes LTV will persist when STV becomes absent. This indicates that STV is indicative of a physiologic substrate necessary for maintaining a state of well-being.

The first indices used to quantify LTV and STV have met with limited success as an indication of fetal outcome [3, 8, 10]. Investigators are now using spectral analysis to determine a better index for variability and its relation to fetal well-being [4, 11, 12]. Spectral analysis differentiates the constituent frequencies which contribute to FHR variability. Theoretically, the periodicity in the FHR due to the respiratory center can be delinated when spectral analysis is applied to a series of consecutive beat-to-beat intervals. This component should be between 30 and 45 cycles per minute which is the approximate respiratory rate of newborns. Because the respiratory center is more sensitive to changes in the oxygen concentation when it is above critical levels, shifts in the frequencey of this periodic component of the FHR might be indicative of the magnitude of the fetal reserve. Preliminary findings have been encouraging [4].

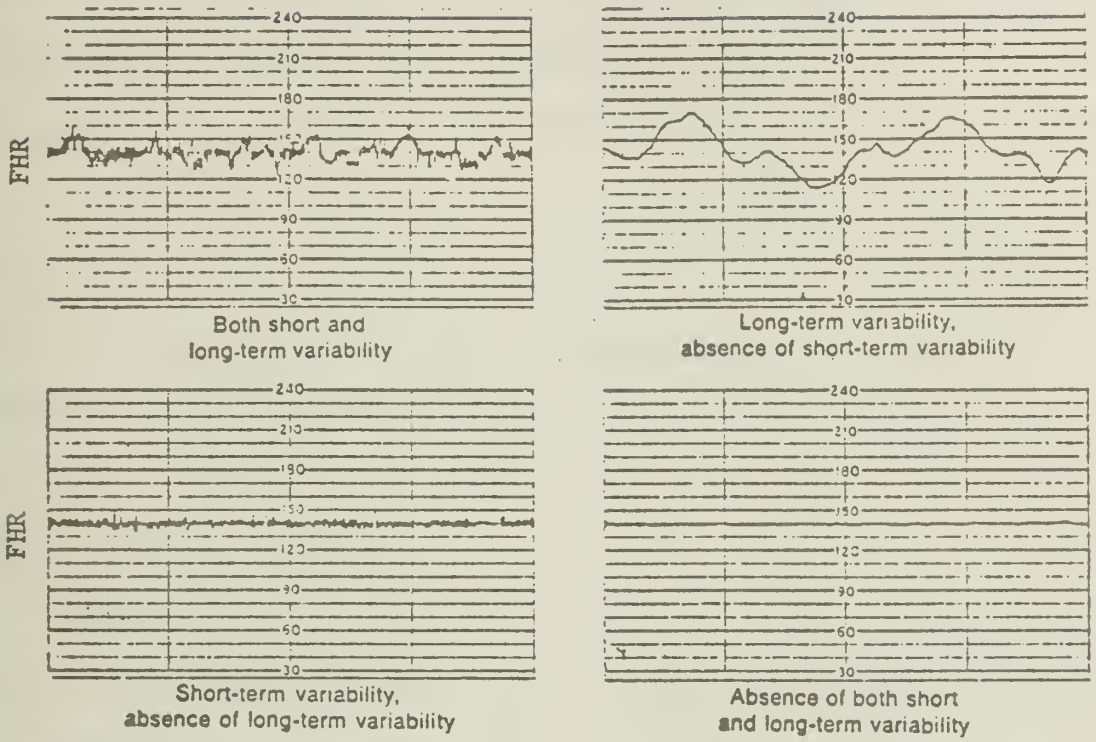


Figure 7. Variations in LTV and STV.
(From Tucker [1])

CHAPTER 3

FETAL HEART RATE MONITORING TECHNIQUES

Ultrasonic, phonocardiographic, and electrocardiographic techniques are often used for FHR monitoring. More esoteric techniques, e.g., magnetocardiographic, have also been explored. The most common antepartum methods utilize ultrasound or the abdominal electrocardiogram (AECG). Intrapartum monitoring usually employs the direct fetal electrocardiogram (FECG).

3.1 Ultrasonic

The ultrasonic technique is often the easiest to use and can provide acceptable rate determinations for periodic pattern and analysis. The technique relies on doppler shifts in a carrier signal (i.e., continuous ultrasound). The signal is generated and the shifts are detected on the maternal abdomen. The shifts are indicative of the mechanical action of the fetal heart and provide a trigger for beat-to-beat rate determinations. However, the signal pulse used for a trigger can vary somewhat thereby introducing artifactual variability in the heart rate. Many researchers have found that this artifactual variability is significant and precludes the use of ultrasonic monitoring techniques for the analysis of STV [1, 2, 8, 9, 13, 15].

Recently, modifications of the ultrasonic technique discussed above have been proposed. These modifications attempt to attenuate the artifactual variability. The first modification of the ultrasonic technique was termed "ranging-autocorrelation Doppler" [16]. While this improved accuracy, the improvement was not of the magnitude necessary to use the technique for STV analysis. The same researchers followed-up with another modification which is claimed to substantially diminish artifactual

variability and allow for STV analysis. This modified technique is termed "directional doppler" [17, 18]. Another alteration to the original ultrasonic technique has been proposed and also is claimed to permit STV analysis. The technique is referred to as "adaptive correlation" [19]. Unfortunately, neither of these last two modified ultrasonic techniques have been quantitatively compared with the direct FECG technique to determine their accuracy.

3.2 Phonocardiographic

This method detects the two major heart sounds in each cardiac cycle and calculates the beat-to-beat interval using these. Because the amplitude of these signals varies, this technique also suffers from artifactual variability and cannot be employed for STV analysis [1, 2, 9, 13, 15].

3.3 Magnetocardiographic

Magnetocardiography has been examined for use in obtaining fetal heart rate determinations free from the type of artifactual variability discussed above [13, 14]. The magnetocardiogram was found to offer a distinct signal pulse for a trigger, but the system requires a low level of magnetic noise to obtain accurate rate determinations. This requirement presently imposes a severe limitation on the application of this technique.

3.4 Electrocardiographic: Intrapartum

The direct fetal electrocardiogram also offers a distinct signal to serve as a trigger. During birth, when there exists sufficient cervical dilation and either spontaneous or artificial amniotomy, an electrode can be attached to the fetal presenting part (most often the scalp). The signal obtained has excellent signal to noise ratio and heart rate can be

determined by detecting the R-peak of the fetal QRS complexes. An accurate calculation of the STV can be made from the changes in this rate.

3.5 Electrocardiographic: Antepartum Detection Procedures

During the antepartum period and in the intrapartum period before the fetal membranes have ruptured, the fetal electrocardiogram must be obtained from electrodes placed on the maternal abdomen. The abdominal electrocardiogram (AECG) has maternal and myoelectric components in addition to the fetal component. The MQRS and myoelectric signals often dwarf the FQRS signal. The average MQRS at the maternal abdomen is 1 mV and the average FQRS is .1 mV. Also, approximately 20% of the maternal beats occur coincident with a fetal beat thereby "masking" the FQRS complex. A bandpass filter can attenuate the influence of myoelectric potentials and noise. However, the frequency domains of the MQRS and FQRS complexes overlap and the maternal beat cannot be removed or significantly attenuated by filtering [2].

Between the 28th and 34th week of gestation, the fetal component of the AECG is severely diminished or absent all together. The reason why the fetal signal diminished is a subject of much discussion, however, it is usually attributed to the development of the vernix caseosa [9]. Between 20 and 28 weeks and from 34 weeks to term, an AECG can be obtained with a good (fetal) signal-to-noise ratio if care is taken in positioning the electrodes.

3.5.1 Correlation and Averaging

When the AECG has a marginal signal-to-noise ratio, cross-correlation and autocorrelation techniques can be used to show the presence of the FECG [20,21]. Also, signal averaging can be used to obtain a good, average FQRS complex [22]. However, neither technique is useful for an

accurate determination of the beat-to-beat rate variability.

3.5.2 Bemmel and Weide

Bemmel and Weide proposed a detection procedure to improve the accuracy of beat-to-beat fetal heart rate determination [24]. The AECG signal is amplified and filtered using a bandpass. The filtered signal is fed into analogue circuitry which uses two voltage thresholds to produce two pulse trains. The series of pulses produced by comparison with the higher threshold indicates the occurance of a maternal or a coincident maternal/fetal R-wave. The second series of pulses indicates the occurrence of potential fetal R-waves in addition to maternal and coincident ones. The use of two thresholds presumes the maternl R-wave is of substantially greater amplitude than the fetal R-wave which is greater than any interference, e.g., myoelectric signals.

All remaining processing is accomplished using digital circuitry. The two pulse trains are compared to produce one train of pulses indicating only fetal R-waves and excluding maternal or coincident R-waves. After a pulse has been produced, the output is disabled for 200 ms. This "dead time", the time during which the output is disabled, presumes the heart rate never exceeds 300 beats per minute (bpm), and is used to reduce the number of false positive detections due to a high amplitude noise peaks.

Each pulse output is used to calculate a potential fetal R-R interval by counting the time between the present and previous pulse. (The time is counted in discrete increments of 3.125 ms.) This R-R interval is compared to the previous one to assure that it is "approximately" equal to the previous interval. "Approximate" equality is defined as the R-R interval being within a plus/minus percentage of the previous interval. The percentage can be varied, however usually $\pm$ 10% during labor and $\pm$ 6% during gestation were found to be "suited values". This comparison of

intervals further reduces the number of false positive detections.

If the R-R interval is approximately equal to the previous one, the newly calculated interval is stored in a register for output purposes. If it is not, the system reinitializes itself by searching for the next two consecutive R-R intervals with the second being approximately equal to the first. When the system is in this re-initialization state, the output register is not updated. The last good rate determination is used as an estimate and is output until the system leaves the re-initialization state, at which time the output register is updated.

Two exceptions are made with regard to entering the re-initialization state. The re-initialization state will not be entered if the R-R interval is equal to approximately twice the previous interval or half the previous interval. The first of these exceptions accomodate fetal beats which occurred coincident with maternal ones and were excluded from the pulse train. The second exception is to further reduce the number of false positive detections, especially those which would cause a rapid degradation of the integrity of the detection procedure.

This procedure can be summarized as follows: A preliminary detection of fetal beats is made using two voltage thresholds. Once a preliminary detection has been made, no others can be made for 200 ms. To be considered a valid fetal beat, the R-R interval calculates using the preliminary detection must be approximately equal to the last good interval calculated. If it is not and the exceptions discussed above do not hold, the procedure enters a re-initialization state. The re-initialization state is exited when two consecutive, approximately equal intervals are found.

3.5.3 Brattle Monitor

The Brattle monitor employs a relatively similar detection procedure as that described above [15]. Although the researchers found this method "to be as accurate as the direct scalp electrode method and more reliable than indirect ultrasound", others have noted that the rate measurements are not sufficiently accurate to permit STV analysis [12].

There are some differences between the two procedures and these will be discussed. Instead of running the AECG through two threshold detectors, the Brattle uses a signal from an electrode on the sternum in addition to the AECG. Maternal beats are detected in the chest ECG using a voltage threshold. This detection produces a gating pulse which is used to remove the maternal and coincident beats from the AECG. The remaining AECG is then filtered and run through a threshold detector. This produces a train of pulses indicating only fetal beats. The pulses are then processed using digital circuitry. This processing is analoguous to that of Bemmel and Weide. However, no mention is made concerning the use of dead time and the authors did not specify the limits of the time period in which the next pulse is expected to occur (Bemmel and Weide use $\pm$ 10% or $\pm$ 6%).

3.5.4 Wheeler, Et Al

Wheeler, et al have proposed a procedure which removes the maternal component from the AECG in a much more sophisticated manner than that used by either of the two procedures above [9]. It involves analogue subtraction of each maternal complex from itself and of the last "maternal-only" complex from a combined maternal/fetal complex. The resultant AECG signal contains only FQRS complexes.

The procedure begins exactly as that of Bemmel and Weide to produce a train of pulses indicating fetal complexes. The R-R interval

determined by the last two pulses in the train is used to calculate a "fetal expectation period" in which the next pulse should occur. This period is equal to ± 10% of the R-R interval. At this point in their processing the two procedures diverge.

In system of Wheeler, et al, a determination of how to perform subtraction now takes place. If a fetal beat was detected in the interval, no modification is made to the subtraction mechanism and the fetal beat passes through unaltered. In its normal state the mechanism subtracts each maternal complex from it self regardless of when it occurs in relation to the fetal expectation period. Also, it simultaneously stores the maternal complex in an analogue storage device which contains 50 samples collected using a 2ms sampling rate. If a fetal complex was not detected in the interval but a maternal complex (i.e., a potential coincident complex) was found, the subtraction mechanism is modified to subtract the previously stored complex from the present one. This subtraction mechanism results in an analogue signal of only fetal complexes which is filtered using a bandpass.

As automatically adjusted voltage threshold, equivalent to 60-65% of the mean fetal R-wave amplitude, is applied to the signal to detect the fetal R-waves and produce a train of pulses. A "dead time" of 300 ms (indicative of 200 bpm) is used to reduce the number of false positives.

In another paper [10] Wheeler, et al discuss using the pulse train to analyze LTV and STV. Before the analysis, two checks were made. First, all R-R intervals exceeding 600 ms (100 bpm) were excluded from the analysis. This exclusion assumes these intervals are indicative of a false negative detections, i.e., missed fetal beats. Second, each R-R interval could vary from the previous one by no more than a specified percentage. This percentage was determined by the researchers for each cardiotachogram.

Any interval exceeding this percentage were also excluded from the analysis. The presumption was that these intervals were due to detection of a false positive with subsequent "non-detection" of the true fetal beat due to the "dead-time".

It is evident that Wheeler, et al have developed a comprehensive FQRS detection procedure. It involves two stages: first, cancellation of maternal component of the AECG and second, detection of the fetal beat. The maternal component is subtracted from AECG leaving only the fetal component. The analogue subtraction mechanism utilizes control signals generated from two threshold detectors and from logic calculating a fetal expectation period. The fetal component of the AECG is then run through an adaptable threshold detector which employs a 300 ms dead time. Finally, each R-R interval must be within a specified percentage of the previous one if it is to be included in the variability analysis.

CHAPTER 4

A NEW ELECTROCARDIOGRAPHIC DETECTION PROCEDURE

This chapter describes a new detection procedure for electrocardiographic FHR monitoring. The procedure uses the AECG as a source signal and is designed to increase the accuracy of beat-to-beat fetal heart rate determinations. The output can be a pulse train indicating fetal R-wave detection and/or the R-R interval in milliseconds to be used for additional processing.

The complete detection procedure is implemented in software thereby facilitating the development, utilization, and possible future improvement of more sophisticated detection methodology than has been previously employed. The software is intended to be executed on a microprocessor-based instrument [25]. It is written in PAL8 [1] assembly language and occupies approximately 2.5K words with an additional 1.5K words for buffers and variable storage. The program is modularized, separating the decision processes so that each can be modified with a minimum of code alteration.

4.1 Procedure Overview

The detection procedure described in this chapter uses two voltage thresholds and a "fetal expectation period" in a similar manner as the procedures discussed in the preceding chapter (section 3.5). Although the procedure does not use "dead time", it does employ the image processing techniques of feature extraction and waveform recognition to reduce the number of false positive fetal R-wave detections.

The program is divided into four basic routines (Figure 8):

[1] This is the assembly language for the PDP8/e minicomputer (Digital Equipment Corporation, Maynard, Massachusetts).

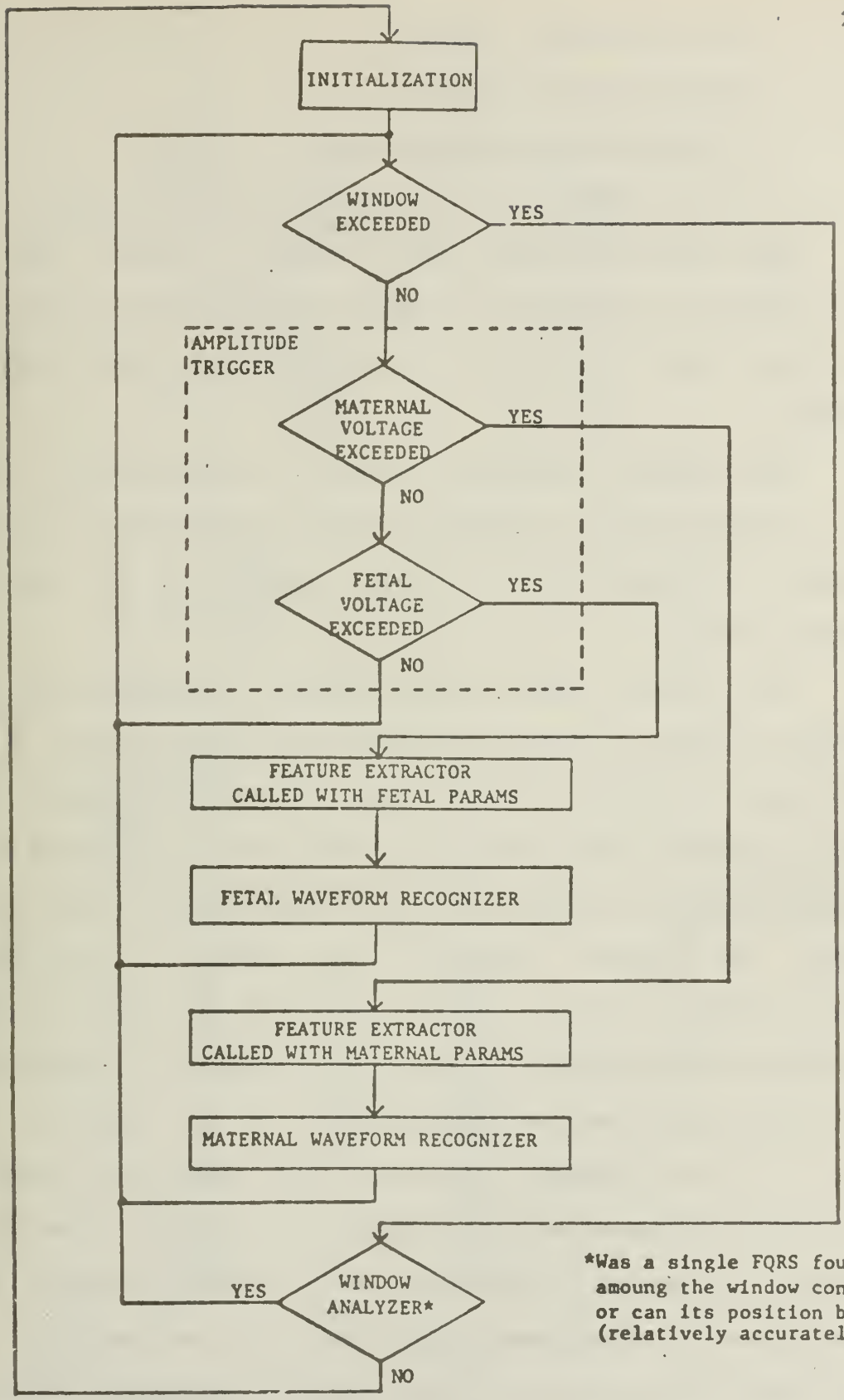


Figure 3. General flowchart of program logic.

1) the amplitude trigger,

2) the feature extractor,

3) the waveform recognizer, and

4) the window (or "fetal expectation period) analyzer.

Each routine performs a check to assure a potential FQRS meets certain specified parameters. A potential FQRS must pass all four checks for a fetal R-wave detection. The following paragraphs outline the processing.

Before digital processing, the AECG is amplified and filtered using a 10-15Hz bandpass (the typical signal is illustrated in Figure 9). The signal is then digitized at a rate of 1 sample/ms and the samples are stored in a buffer.

The amplitude trigger routine analyzes the digitized AECG samples performing preliminary detection and classification of a waveform as a FQRS or MQRS using two voltage thresholds. When the amplitude trigger routine detects a potential FQRS or MQRS, the feature extractor is called with the appropriate parameters necessary to extract the slopes of the FQRS and MQRS waveform. The extracted slopes are then checked by the appropriate waveform recognizer. If the recognizer finds that the slopes constitute a proper FQRS or MQRS waveform, the appropriate information is stored for use by the window analyzer and the program returns to the amplitude trigger routine. If the recognizer finds that the slopes do not constitute a proper FQRS or MQRS waveform, the waveform is considered noise/artifact, appropriate information is stored for use by the window analyzer, and the program returns to the amplitude trigger routine. The amplitude trigger routine resumes the search for the next potential FQRS or MQRS waveform

The window analyzer examines the contents of a specified time window, i.e., time interval. This window is calculated from the preceding

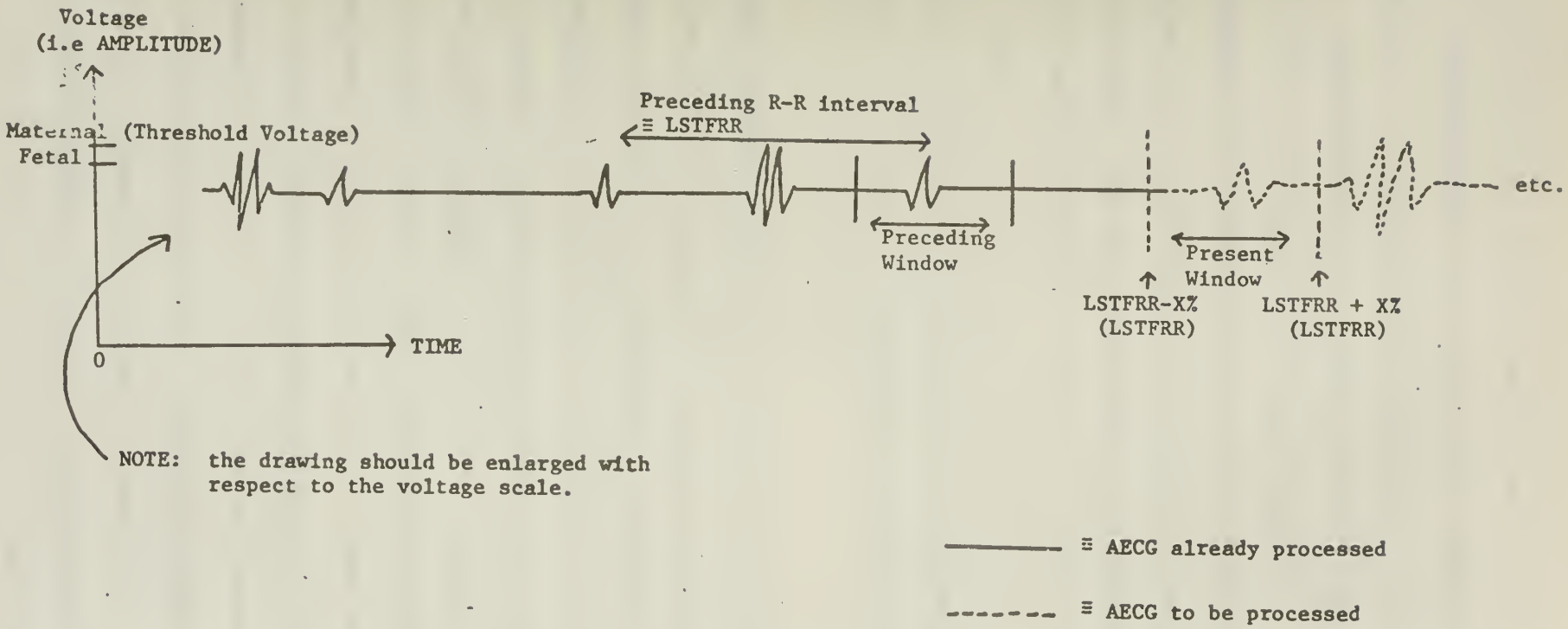


Figure 9. Schema of FQRS window determination.

fetal R-R interval (Figure 9). The window analyzer is called by the amplitude trigger routine when the window has been exceeded. If the contents of the window include a single FQRS, a new window is determined using the R-peak of this FQRS and that of the previous one. Also, parameters crucial for fetal R-wave detection are adjusted to reflect the characteristics of this FQRS. Therefore the parameters can be adapted to allow for fetal R-wave detection when the FQRS waveform is diminishing in intensity. After appropriate modification of the parameters and determination of the next window, the program returns to the amplitude trigger routine.

The above is a general description of how the program processes the AECG. A more detailed discussion follows.

4.2 Initialization

The program begins by searching for two FQRS waveforms, each of which meet operator specified parameters designating acceptable amplitude, slope characteristics, and waveform characteristics. After the second FQRS is found, a check is made to assure that the FQRS waveforms were consecutive, i.e., no MQRS or artifact waveforms were found between them. This check is made because such a MQRS or artifact waveform might be coincident with, and therefore be masking a FQRS waveform which occurred between the two detected ones. If the waveforms are not consecutive, the initialization attempt will be aborted, and searching will continue for the next FQRS. If the FQRS waveforms are consecutive, the R-R interval will be determined and used to calculate the first time window where the next FQRS should occur. Also, the parameters which are crucial for fetal R-wave detection are modified appropriately to reflect the characteristics of the FQRS waveforms which were found.

4.3 Amplitude Trigger

There are two voltage thresholds with the lower one being program - adjustable. The amplitude trigger routine is based on the presumption that: 1) any waveform which exceeds both the lower and upper thresholds is a MQRS waveform, 2) any waveform which exceeds only the lower threshold is a FQRS waveform, and 3) any waveform not reaching the lower threshold is considered artifact and can be ignored. Therefore, a preliminary classification of a waveform as noise, FQRS, or MQRS is made using the maximum amplitude achieved.

When either a potential FQRS or MQRS waveform is detected (i.e., first zero crossing) by the amplitude trigger routine, a jump is made to the appropriate program subsection which will call the feature extractor and perform waveform recognition.

4.4 Feature Extraction

The feature extractor subroutine searches a finite number of digitized samples extracting slopes meeting the specified slope parameters. These parameters are expressed as amplitude (i.e., voltage) and time duration minimums which must be exceeded (Figure 10). There are minimums for each sequential slope to be extracted. There are two sets of these slope parameters: one for potential FQRS waveforms and the other for potential MQRS waveforms.

The parameters for the feature extractor subroutine include the following:

1) a pointer to the digitized sample from which to begin searching for slopes.
2) the number of samples to be searched, and
3) the set of slope parameters to be used

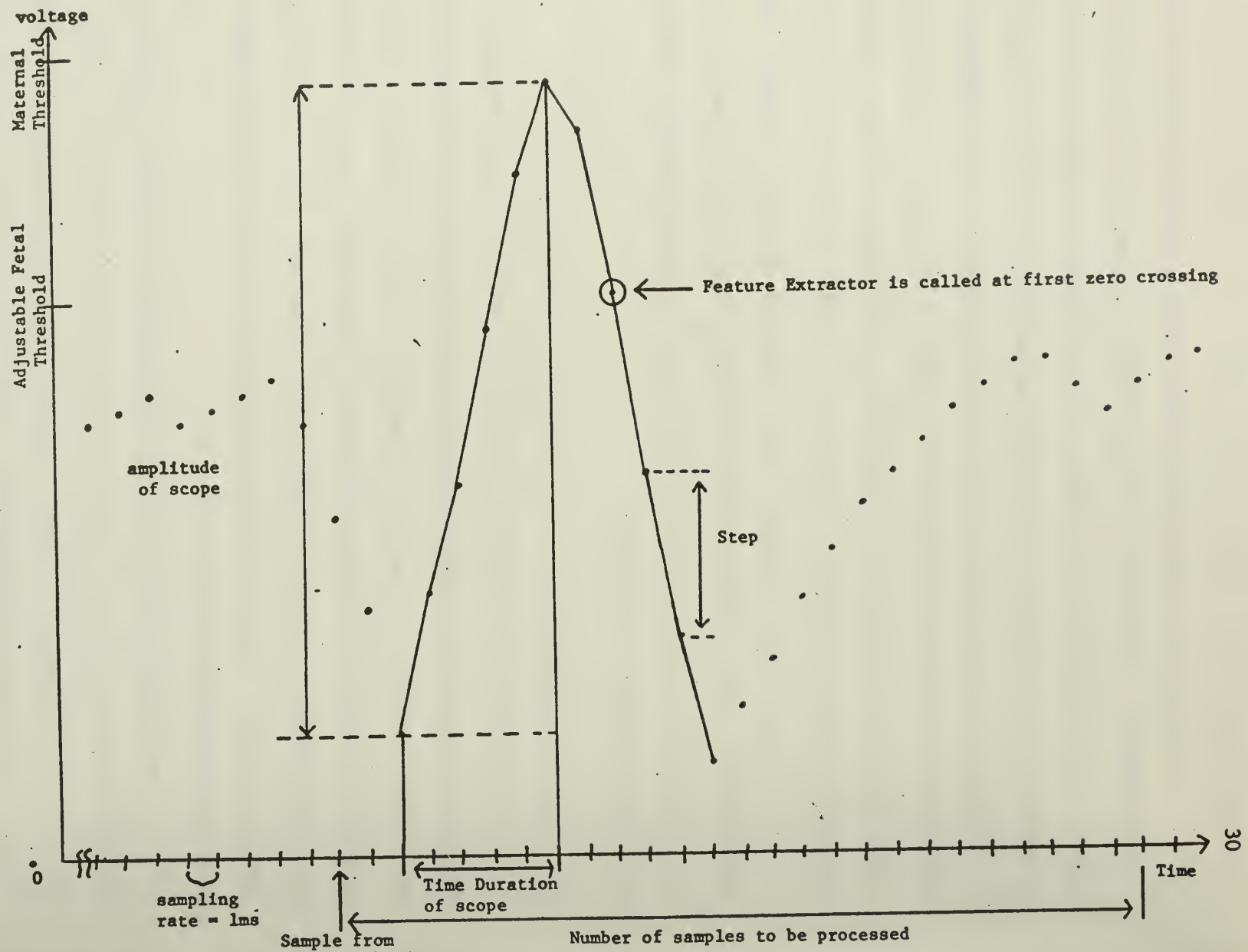


Figure 10. Schema of feature Extraction.

(fetal or maternal).

The extraction of slopes begins by subtracting sequential samples values to form a series of differences. Each of the differences is compared to a threshold and those exceeding the threshold are noted. A difference which exceeds the threshold is called a "step". Consecutive "steps" of the same sign are considered a slope.

After "extraction" (identification), a slope is compared to the slope parameters. If the appropriate slope parameters are met, information concerning the slope is stored for use by the waveform recognizer and search for a sequential slope starts.

The extraction process terminates with any of the following conditions:

1) no slopes were extracted which met the parameters for the first slope of the waveform,
2) one or more slopes were extracted which did meet the appropriate parameters, but another sequential slope was found which did not meet its appropriate parameters, or
3) one or more slopes were extracted which did meet the appropriate parameters, but another sequential slope was not found. Upon termination of the extraction process, the feature extractor subroutine returns control to the calling routine.

4.5 Waveform Recognizer

The waveform recognizer compares the cummulative characteristics of the slopes extracted with waveform parameters to arrive at the final decision as to the classification of the waveform. For the potential MQRS waveform these parameters include a minimum and maximum number of slopes, a

maximum width (measured from Q to S peaks), and whether the R-peak occurred within the window. If the cummulative characteristics meet the parameters, information is stored concerning this FQRS for use by the window analyzer.

If one or more of the parameters are not met, the waveform is considered to be artifact/noise. This artifact/noise waveform might potentially be masking a coincident FQRS, i.e., the waveform masks some portion of the window and potentially the FQRS might occur in this same portion of the window. The part of the waveform which is contained in the window, i.e., the part masking the window, is called a "mask". Any part of the artifact/noise waveform outside of the window is ignored.

The waveform recognizer compares the width of the mask with a width threshold. Masks with widths less than the threshold are termed "narrow" and those greater are termed "wide". This distinction is made because a narrow mask allows for a sufficiently accurate estimate of the location of the R-peak to be made so that the window analyzer can calculate a new window. However, a wide mask does not allow a sufficiently accurate estimate of the location of the fetal R-peak to be made and a new window cannot be determined with any degree of certainty. Therefore, the procedure must enter the initialization routine to calculate a new window.

For the potential MQRS waveform, the parameters are a minimum and maximum number of slopes, and a maximum width. Since the window is calculated from the fetal R-R interval, the maternal R-peak need not necessarily occur within the window. Any potential MQRS waveform which does not meet these parameters is considered to be an artifact/noise waveform, and it is analyzed as above. If the MQRS waveform meets the parameters, analysis also proceeds as it does for the artifact/noise waveform. In the present version of the program, the MQRS is not cancelled when detected, hence it can be considered as an artifact/noise waveform

which potentially be masking a coincident FQRS.

After classifying the waveform as a FQRS, "narrow" mask, or "wide" mask, the waveform recognizer returns control to the amplitude trigger.

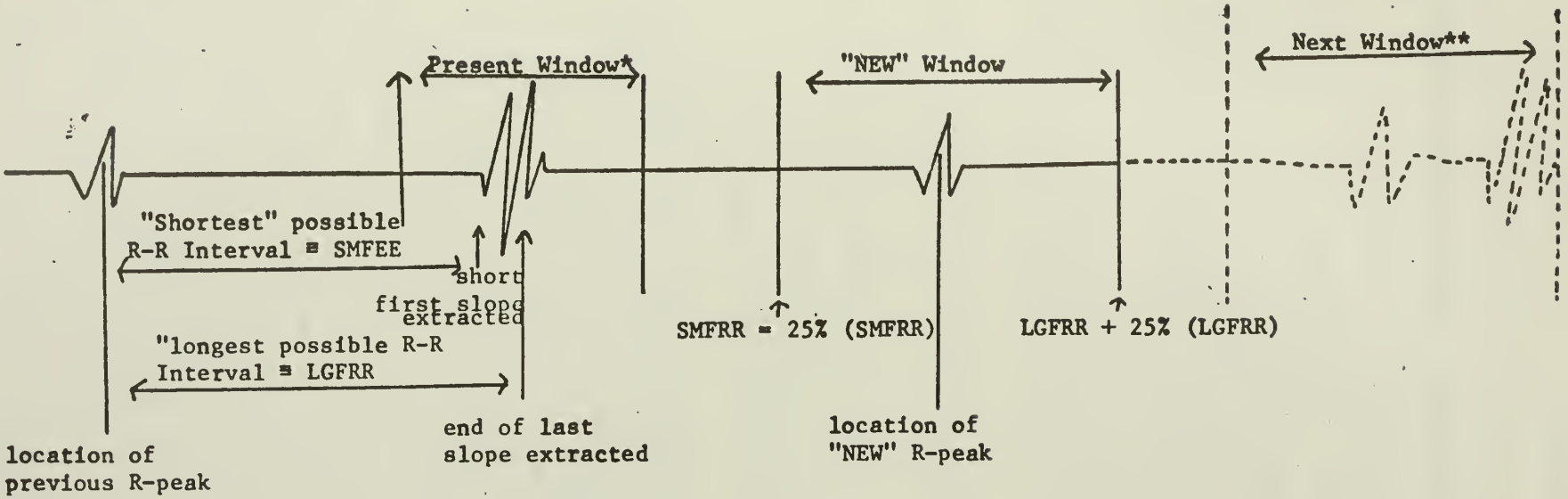
4.6 Window Analyzer

The window analyzer examines the contents of the window. Information concerning the contents is compiled by the waveform recognizer. The contents of the window can be grouped as follows:

1) a single FQRS waveform in addition to zero or more potential masks,
2) two or more FQRS waveforms in addition to zero or more potential masks,
3) only one narrow mask,
4) any combination narrow and wide masks, or
5) nothing.

If the contents of the window include a single fetal beat, the R-R interval is calculated and a new window determined. Also, the parameters which are crucial for fetal R-wave detection are modified to reflect the characteristics of this FQRS waveform. These crucial parameters are the fetal voltage threshold, the slope amplitude minimums, and the width of the FQRS waveform.

If the window contains only one "narrow" mask, the shortest and longest possible R-R intervals are calculated and a new window is established using these intervals (Figure 11). If this new window contains a single FQRS waveform, the shortest and longest R-R intervals will be calculated again and the next window will be determined (Figure 11). However, should the new window only contain a "narrow" mask, no attempt



* The present window only contains a "narrow" mask, in this case a MQRS.

** The lower and upper boundaries of the next window are calculated similar to those of the new window, except that a new SMFRR and LGFRR are calculated using the location of the new R-peak.

Figure 11. Schema of window calculation for occurrence of a narrow mask.

will be made to establish the next window. Rather, the program will return to the initialization code, search for the next two consecutive FQRS waveforms, and determine a new window using their R-R interval.

Whenever a window does not contain a single FQRS waveform or only one "narrow" mask, the program will return to the initialization routine for the establishment of new window.

4.7 Program States

The logic of the detection procedure will now be reviewed via the conceptualization of various "program states" (Figure 12). In the INITIALIZATION1 and INITIALIZATION2 states, amplitude, slope characteristics and waveform characteristics are utilized to detect FQRS waveforms. When the DETECT state is entered, a window is established using the R-R interval. After leaving the INITIALIZATION states, the window is also utilized for the detection of fetal beats.

While the program remains in the DETECT state, the window is established using the standard method (i.e., based on the R-R interval and the output is the actual R-R interval. However, when the program enters the COMPROMISE1 state or exits the COMPROMISE1 state/enters the DETECT state, a modified method is used for calculation of the R-R interval, and the output is an estimated R-R interval using the middle of the narrow mask.

Whenever the program enters the MULTIPLE DETECTION, WIDE MASK, NOTHING FOUND, or COMPROMISE2 state, the integrity of the detection procedure is considered to be critically compromised. In any of these states the establishment of a window would be almost arbitrary because the location of the fetal R-peak cannot be estimated with a sufficient degree of certainty. Therefore, the program returns to the INITIALIZATION states

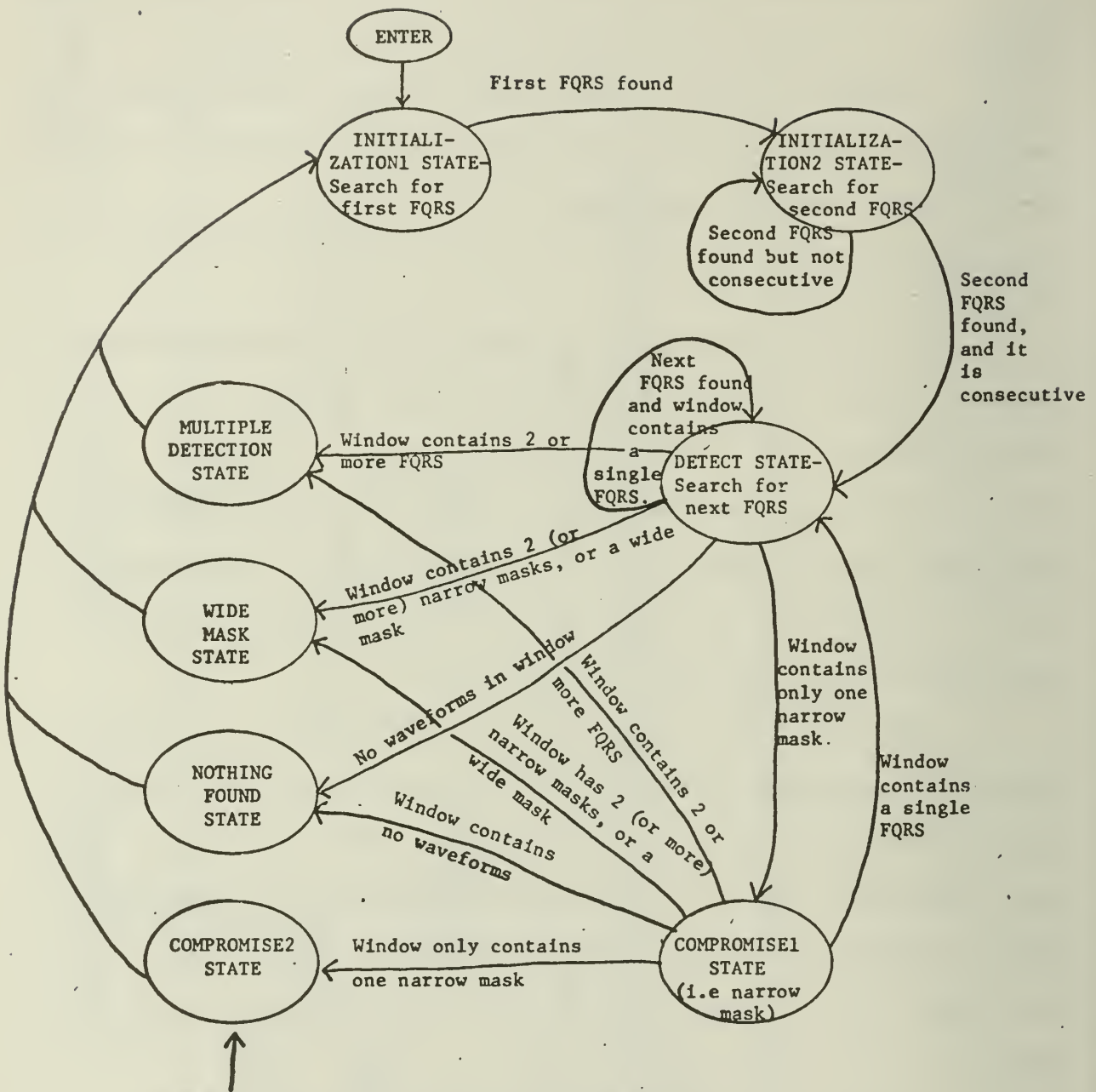


Figure 12. Program state diagram.

for the determination of a new window. There is no output.

4.8 Comparison with Other Electrocardiographic Detection Procedures

There are three salient differences between the detection procedure outlined in this chapter and those described in the previous chapter (section 3.5). The first is the implementation of the procedure in software to be executed on a microprocessor-based instrument. This povides the procedure with flexibility and versatility, and it permits easy modification of the procedure during developmental stages. This is potentially the most important difference.

The second salient difference is the use of feature extraction and waveform recognition to decrease the number of false positive detections. In the other procedures noise of sufficient amplitude could trigger a false positive detection. However, in the detection pocedure discussed in this chapter, the noise spike must also meet slope and waveform parameters to be detected as a FQRS.

The third significant difference involves how the window or "fetal expectation period" is utilized. The procedure described in this chapter continues processing until the window is exceeded, at which time the contents of the window are analyzed. Therefore, the decision to make a fetal R-wave detection is delayed, allowing more information to be compiled. This additional information allows a decision to be made with greater certainty. Also, although waveforms outside the window are detected, they are ignored. Hence, it is not necessary to use "dead time".

The procedures discussed in the previous chapter do not continue processing until the window is exceeded and do not ignore detections occurring outside of the "expectation period". The first detection, whether actual fetal R-peak or artifact/noise, is used and "dead time" is

used to decrease the number of false positive detections. Therefore, these procedures can suffer from false positive detections followed by false negative detections due to the FQRS occurring during the dead time. Although the obvious occurrences of this situation can be excluded from variability analysis as Wheeler, et al did (see section 3.5.4), it is almost impossible to determine those instances when a false positive precedes the true FQRS by a small margin.

The procedure described in this chapter is not susceptible to the pitfall just discussed because a false positive detection followed by the true detection within the same window forces the program into the MULTIPLE DETECTION state. When this state is entered, the associated R-R intervals can be excluded from variability analysis.

CHAPTER 5

CONCLUSION

The AECG from a patient in labor has been analyzed using the procedure described in the previous chapter and the results are promising. With the incorporation of MQRS waveform cancellation (Appendix II) the procedure is expected to afford the accuracy necessary to perform analysis of LTV and STV.

There exists the possibility that the number of false negative detections might be increased significantly over the number produced by the other procedures discussed in Chapter 3 (section 3.5) due to the more stringent criteria for detection imposed by the new procedure outlined in this paper. However, this should rarely occur because the crucial parameters are adjusted with each detection. The final research analysis of the significance of this possible problem awaits quantification of the number of false negatives in a signal free of the maternal component.

Future research should be conducted to develop a program which examines a segment of input data and calculates the initial parameters for feature extraction and waveform recognition. Presently it is required that the operator technician supply all initial parameters. While this might suffice in a research environment, it consumes considerable time and would not be appropriate for practical application.

Also, research exploring lead positioning would be advantageous. The research of Oldenburg and Masklin [23] suggests that the maternal abdomen behaves as a uniform conductor between 20 and 28 weeks. While from 34 weeks to gestation, there appears to be a preferred pathway. They propose two different lead systems to maximize the fetal component of the AECG, one for each period. These systems should be analyzed for use with

the new detection procedure.

During the period from 28 to 34 weeks, the fetal component of the AECG significantly diminishes. When this occurs, it will be necessary to rely on the other monitoring techniques (e.g., ultrasonic).

Researchers have suggested that microprocessor technology be utilized to implement detection procedures in software [19], for data acquisition, reductory and presentation of [26], and to provide the relevant information at reduced costs [2]. A microprocessor-based instrument incorporating the detection procedure described in this paper and a program for performing STV spectral analysis could potentially serve all of these functions.

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APPENDIX I

CONTROL OF FETAL HEART RATE
(From Tucker [1])

Fetal factors regulating heart rate	*Location*	*Action*	*Effect*
Parasympathetic division of autonomic nervous system	Vagus nerve fibers supply sinoatrial (SA) and atrioventricular (AV) node	Stimulation causes release of acetylcholine at myoneural synapse	Decreases heart rate Maintains beat-to-beat variability
Sympathetic division of autonomic nervous system	Nerves widely distributed in myocardium	Stimulation causes release of norepinephrine at synapse	Increases FHR Increases strength of myocardial contraction Increases cardiac output
Baroreceptors	Stretch receptors in aortic arch and carotid sinus	Responds to increase in blood pressure by stimulating stretch receptors to send impulses via vagus or glossopharyngeal nerve to midbrain producing vagal response	Decreases FHR Decreases blood pressure Decreases cardiac output
Chemoreceptors	Peripheral—in carotid and aortic bodies	Responds to a marked peripheral decrease in oxygen and increase in carbon dioxide	Produces bradycardia sometimes with increased variability
	Central—in medulla oblongata	Central chemoreceptors respond to decreases in O_2 and increases in CO_2 in blood and/or cerebrospinal fluid in this area	Produces tachycardia and increase in blood pressure with decrease in variability
Central nervous system	Cerebral cortex	Responds to fetal movement	Increases variability
		Responds to fetal sleep	Decreases variability
	Hypothalamus	Regulates and coordinates autonomic activities (sympathetic and parasympathetic)	
	Medulla oblongata	Mediates cardiac and vasomotor reflex center by controlling heart action and blood vessel diameter	Maintains balance between cardioacceleration and cardiodeceleration

Fetal factors regulating heart rate	*Location*	*Action*	*Effect*
Blood volume	Fluid shift between capillaries and interstitial spaces	Responds to elevated blood pressure by causing fluid to move out of capillaries and into interstitial spaces	Decreases blood volume and blood pressure
		Responds to low blood pressure by causing fluid to move out of interstitial space into capillaries	Increases blood volume and blood pressure
Intraplacental pressures	Intervillous space	Fluid shift between fetal and maternal blood is based on osmotic and blood pressure gradients; maternal blood pressure is about 100 mm Hg and fetal BP about 50 mm Hg; therefore, balance is probably maintained by some compensatory factor	Regulates blood volume and blood pressure
Frank-Starling mechanism	Mechanism based on stretching of myocardium by increased inflow of venous blood into right atrium	In the adult the myocardium is stretched by an increased inflow of blood, causing the heart to contract with greater force than before and pump out more blood; the adult then is able to increase cardiac output by increasing heart rate and stroke volume; this mechanism is not well developed in the fetus	Cardiac output is dependent on heart rate in the fetus: ↓ FHR = ↓ Cardiac output ↑ FHR = ↑ Cardiac output

Fetal factors regulating heart rate	*Location*	*Action*	*Effect*
Hormonal regulation	Adrenal medulla	Releases epinephrine and norepinephrine with severe fetal hypoxia producing sympathetic response	Increases FHR Increases strength of myocardial contraction Increases cardiac output
	Adrenal cortex	Low fetal blood pressure stimulates release of aldosterone, decreases sodium output, increases water retention, which increases circulating blood volume	Maintains homeostasis of blood volume

APPENDIX II

INCORPORATION OF MQRS WAVEFORM CANCELLATION

The program described in Chapter 4 does not presently have the logic necessary to cancel the maternal component of the AECG although potential occurrences of coincidence are detected. A subtraction system similar to that used by Wheeler, et al [9] can be easily added to the detection procedure. Memory requirements will increase to accomodate the code for subtraction and buffer space to hold QRS waveforms.

Subtraction of the last "maternal-only" waveform from a possible coincident waveform would occur when the window analyzer does not find a fetal waveform in a window which contains a meternal waveform. This requires modification of the waveform recognizer so that maternal waveforms will not be processed as artifact/noise. After subtraction, the feature extractor and fetal waveform recognizer can be used to determine if the remaining values constitute a fetal waveform.

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222 Digital Computer Lab
University of Illinois
Urbana, IL 61801

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15. Supplementary Notes

16. Abstracts

A computer program is described which accepts as input the signal from abdominal electrodes amplified and dipped. The program extracts the fetal QRS signal and provides the beat-to-beat period.

Although the program design is general, it is directed toward use in a fully portable instrument employing a CMOS microprocessor (Intersil IM6100) at the cone of the instrument.

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medical instrument, fetal cardiac, cardiac analysis

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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